ABSTRACT

A program is being performed under the sponsorship of the United States Department of Energy, Office of Industrial Technologies, to improve the performance of stationary gas turbines in cogeneration through the selective replacement of metallic hot section components with ceramic parts. The program focuses on design, fabrication, and testing of ceramic components, generating a materials properties database, and applying life prediction and nondestructive evaluation (NDE). The development program is being performed by a team led by Solar Turbines Incorporated, and which includes suppliers of ceramic components, U.S. research laboratories and an industrial cogeneration end user.

The Solar Centaur 505 engine was selected for the development program. The program goals included an increase in the turbine rotor inlet temperature (TRIT) from 1010°C (1850°F) to 1121°C (2050°F), accompanied by increases in thermal efficiency and output power. The performance improvements are attributable to the increase in TRIT and the reduction in cooling air requirements for the ceramic parts. The ceramic liners are also expected to lower the emissions of NOx and CO.

Under the program uncooled ceramic blades and nozzles have been inserted for currently cooled metal components in the first stage of the gas producer turbine. The louver-cooled metal combustor liners have been replaced with uncooled continuous-fiber reinforced ceramic composite (CFCC) liners. Modifications have been made to the engine hot section to accommodate the ceramic parts.

To-date all first generation designs have been completed. Ceramic components have been fabricated, and are being tested in rigs and in the Centaur 505 engine. Field testing at an industrial co-generation site was started in May, 1997. This paper will provide an update of the development work and details of engine testing of ceramic components under the program.

INTRODUCTION

Because of their superior high temperature durability, the application of ceramics as structural materials for gas turbine hot section components will enable a significant increase in the turbine rotor inlet temperature (TRIT) of current all-metal industrial gas turbines, resulting in improved thermal efficiency, greater output power, and reduced emissions of NOx and CO. The U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT), therefore, initiated in September of 1992 a program aimed at developing and demonstrating a ceramic stationary gas turbine.
(CSGT) for cogeneration operation. Solar Turbines Incorporated (Solar) is the prime contractor on the program which includes participation of major ceramic component suppliers, nationally recognized test laboratories, and an industrial cogeneration end user.

Phase I of the program, started in September of 1992, involved concept and preliminary engine and component design, ceramic materials selection, technical and economic evaluation, and concept assessment. The work in Phase II, started in April of 1993, focuses on detailed engine and component design, ceramic specimen and component procurement, testing, and the development of appropriate non-destructive technologies for part evaluation, and component life prediction. Phase III of the program revolves around two consecutive engine tests at an industrial cogeneration site.

Previous summaries of the work performed under the CSGT program have been reported (van Roode et al., 1993, 1994, 1995, 1996, 1997). This paper summarizes the recent Phase II development work, in-house ceramic component engine testing and field testing at ARCO Western Energy in Bakersfield, California.

TECHNICAL APPROACH

The technology base for the CSGT program is provided by the advancements in ceramic component fabrication knowledge developed under past ceramic turbine programs, such as the Advanced Gas Turbine (AGT) Program and the Advanced Turbine Technology Applications Program (ATTAP) of the U.S. Department of Energy, Office of Transportation Technologies. The program strategy provides a strong focus on near-term ceramic turbine technology demonstration and lowering barriers for its acceptance by the marketplace. Applications include retrofitting existing gas turbine installations and incorporating ceramic component technologies in future engine designs. The ceramic turbine technology under development in this program is a key enabling technology to realize the performance and environmental goals of the Advanced Turbine Systems (ATS) program, a broad initiative of the U.S. Department of Energy, Office of Fossil Energy, and Office of Energy Efficiency and Renewable Energy, to develop the next generation of high performance gas turbines for utility and industrial applications (Report to Congress, 1994).

Figure 1 is a schematic of the Solar Centaur 50S, the engine selected for ceramic insertion under the CSGT program. The baseline metal engine has a rated shaft thermal efficiency of 29.6% and an electrical output rating of 4144 kW and is fitted with a SoLoNoX dry, low NOx combustion system. The gas producer turbine of the all-metal Centaur 50S has two stages and the power turbine has one stage. A single-shaft configuration was selected for the development engine.

The Centaur 50S is being retrofitted with first stage ceramic blades and nozzles, and a ceramic combustor liner. The engine hot section is being redesigned to adapt the ceramic parts to the existing metallic support structure. Accompanying the ceramic insertion the Centaur 50S is being uprated from its current TRIT of 1010°C (1850°F) to a TRIT of 1121°C (2050°F). The performance improvement goals include a relative increase in the electrical thermal efficiency of 5.6% in simple cycle and 5.3% in cogeneration, and an increase in the electrical output from 4144 kW to 5217 kW, representing a relative increase of about 25.9%. Newer engines of the all-metal Centaur 50S meet NOx emissions levels of 25 ppmv over the 50 to 100 percent load range. Under the program NOx emission levels of 25 ppmv or below must be demonstrated and have the potential for NOx levels of 10 ppmv or better. No CO target level was required for the program, but Solar has set a CO target of 25 ppmv. Predicted engine performance data have been reported previously (van Roode, et al., 1994).

Solar's approach to incorporating ceramics for industrial gas turbine design attempts to minimize the risks inherent in a still immature technology by using a set of guidelines which are consistent with current ceramic design practice. These include limiting the number of ceramic components, using proven ceramic design practice from past programs, selecting well characterized and promising candidate ceramic materials with potential for cost-effective scale up to production applications, iterative testing with stepwise increases in firing temperatures to a modest final design TRIT, and

![FIG. 1 - SOLAR 50S GAS TURBINE WITH COMPONENTS TARGETED FOR CERAMIC INSERTION](https://asmedigitalcollection.asme.org/GT/proceedings-pdf/GT1998/78668/V005T13A005/4218687/v005t13a005-98-gt-181.pdf)
minimizing transient and steady state stresses in the ceramic components and adjacent metal structures. The CSGT program aims to achieve early demonstration of component designs in an engine rig which duplicates all the conditions the ceramic components will experience during actual engine operation.

Solar's industrial gas turbines must be able to operate continuously without interruptions other than those resulting at scheduled maintenance for 30,000 hours which is the typical time before overhaul (TBO). Ceramic components must therefore have design lives consistent with the expected TBO life. Since the ultimate field test goal for the program was 4000 hours, and to minimize the materials and design changes to the current metal engine, a design life target of 10,000 hours was selected for the engine and its components for the program.

Figure 2 illustrates the integrated design and test philosophy of the CSGT program. In this design approach, design analysis was iterated with life prediction, testing, and post-test component evaluation. In the first stage simulated components were tested in rigs to prove key design concepts such as blade and nozzle attachment configuration, blade root compliant layers, and interfacing of ceramics to metallic support structures. In the second stage the findings from these tests were fed back into the design of first ceramic component prototypes which were then tested in a Centaur 505 engine modified to accept the ceramic parts. The results of the engine tests were then used to modify the ceramic part designs to the extent desired. In the final stage second generation parts with superior performance are being used for the field testing in Phase III of the program.

ENGINE/COMPONENT DESIGN AND MATERIAL SELECTION

Figure 3 shows a cross section of the hot section of a Centaur 505 gas turbine, the gas turbine selected for ceramic insertion under the CSGT program, with a ceramic composite combustor liner, ceramic nozzles and ceramic blades. Detailed design information regarding these components has been presented in prior papers (Norton, et al., 1995, van Roode et al., 1995, 1996, 1997).

**Combustor Design**

The use of a ceramic gas turbine combustor is associated with two advantages over a conventional metal combustor: firing temperature can be increased without degrading combustor durability, and emissions from lean premixed gas turbine combustors can be reduced using a "hot wall" (Smith, et al., 1996, 1997). Air saved from reduced cooling requirements for the combustor wall can be used to lean out the flame in the primary zone resulting in lower emissions of NOx. A second emission benefit is a reduction in CO quenching near the combustor wall.

The existing SoLoNOx combustor of the Centaur 505 engine was modified by integrating the ceramics in the linear sections of the combustor. The ceramic combustor was designed to be fully interchangeable with the
production Centaur 50S dry low-NOX lean-premix (SoLoNox) combustor. The all-metal combustor is an annular, axial flow combustor that utilizes twelve premixing natural gas injectors. Through lean premixed combustion, NOx and CO emissions are limited to less than 25 ppmv and 50 ppmv, respectively, at the 1010°C design turbine rotor inlet temperature (TRIT) of the Centaur 50S engine.

The ceramic hot section layout of Figure 3 shows the main design features. The combustor is comprised of a metallic dome section at the upstream end, two concentric ceramic cylinders (in metal housing) that form the combustor primary zone, and two conical, metallic exit sections. The dome and exit sections are film cooled and are essentially identical to their all-metal production engine counterparts. A layer of compliant insulation between the ceramic liner parts and the metal housing minimizes radial contact stresses. All pressure loads are carried by the metal housing. The inner and outer ceramic cylindrical liners are 33 cm and 75 cm in diameter, respectively, and are 20 cm long. Their wall thickness is approximately 0.2-0.3 cm. The ceramic liners replace louver-cooled Hastelloy X liners in the Centaur 50S combustor.

The material of choice for the ceramic liners was a continuous fiber-reinforced ceramic composite (CFCC) with a silicon carbide based fiber (Nicalon) fabricated by Nippon Carbon Company of Japan as reinforcement in a silicon carbide matrix incorporated by chemical vapor infiltration. CFCC's were selected because of their superior fracture toughness which gives them a distinct advantage over monolithics for large structures such as the combustor liners of the Centaur 50S engine. The current combustor liner material is the enhanced SiC/SiC CFCC of Dupont Lanxide Composites, Inc. (DLC). A set of these enhanced SiC/SiC CFCC liners, shown in Figure 4, was acceptance tested for 100 hours in the CSGT Centaur 50S gas turbine, in preparation for field testing at ARCO Western Energy in Bakersfield, California. The actual materials selection process and supporting subscale component testing has been described elsewhere (van Roode, et al., 1996, Simpson, et al., 1997).

**FIG 4 - ENHANCED SiC/SiC CFCC COMBUSTOR LINERS FABRICATED BY DuPONT LANXIDE COMPOSITES**

**Nozzle Design**

Under the CSGT program first stage all metal FS-414 nozzles are being replaced with ceramic parts. The cooled nozzles are coated with a Pt,Rh-aluminide diffusion coating. The ceramic nozzle design is significantly different from the metal nozzle. It is uncooled and single vane compared to the two-vane cooled metal nozzle, and the tip seal has been decoupled (a metal tip seal is attached to the nozzle case). These design changes were made to simplify the fabrication of the ceramic components. The nozzle attachment has been modified to accommodate the ceramic-to-metal interface to the first stage diaphragm. The number of nozzles was increased from 15 two-vane segments to 42 single-vane segments based on the results of a vibration analysis.

The ceramic nozzle airfoil is different from the metal airfoil as well. Finite element stress/temperature analysis and life prediction showed that replacing the metal airfoils with a ceramic vane of the same geometric configuration would result in an unacceptably high stress level incompatible with long service life. The airfoil chord was therefore reduced in half and the airfoil was bowed axially and tangentially compared to the current cooled metal nozzle. The redesign resulted in a significant drop in the maximum steady state stress levels from about 480 MPa to about 162 MPa at the estimated "hot spot" temperature at the vane trailing edge of 1288°C (2350°F). The stress levels were calculated using SN-88 silicon nitride (NGK Insulators, Ltd.), the material selected for nozzle fabrication. The cooled metal FS-414 nozzle and the SN-88 silicon nitride nozzle are shown in Figure 5. SN-88 was selected since it met the design requirements for slow crack growth and creep which are believed to be life-limiting. A nine-hour test was successfully conducted on 42 SN-88 nozzles in the CSGT Centaur 50S developmental gas turbine at Solar. A second test of the nozzle with minor design modifications is planned for March 1998.

**FIG 5 - COOLED FS-414 METAL AND UNCOOLED SN-88 CERAMIC NOZZLES FOR CENTAUR 50S**

**Blade Design**

In accordance with the low-risk design strategy of the CSGT program only the first stage of turbine blades was replaced with ceramic parts. The all-metal Centaur 50S engine has 62 first stage cooled equiaxed MAR-M247 blades coated with a Pt-aluminide diffusion coating for oxidation protection. The CSGT blade design has an airfoil shape that is almost identical to that of the metal blade, except for the absence of cooling passages. The fit tree attachment of the metal blade has been replaced with a conventional dovetail. A compliant layer between blade root and disk buffers the ceramic/metal interface. Maximum steady state stress in the dovetail blade design was estimated at 214 MPa at the blade root neck under the platform at a temperature of 682°C (1260°F).

Based on critical materials properties and life prediction considerations, AS-800 (AlliedSignal Ceramic Components) and SN-281 (Kyocera Industrial Ceramics Corporation) silicon nitride materials were selected for engine testing. Figure 6 shows the cooled metal first stage MAR-M247 blade and an uncooled AS-800 silicon nitride blade. The AS-800 blades were tested for a 100-hour acceptance test in the CSGT Centaur 50S gas turbine in preparation for field testing at ARCO Western Energy in Bakersfield, California.

A significant difference between operation of the Centaur 50S engine with metal and ceramic blades is clearance control. The metal blade is designed for a hot clearance of 0.5 mm which is achieved by applying a rub-tolerant coating to the first stage nozzle tip seal. The ceramic blade has a design hot clearance of 1.3 mm, and is designed to operate with open...
clearances. Operating the engine with this wide clearance results in a performance loss. To fully realize the benefits of operating the engine with ceramic blades and nozzles will require the development of lip seals with abradable coatings that can accommodate a rub by ceramic blade tips. Development of abradable coatings is ongoing under other Solar development programs.

Secondary Component Design

A significant redesign effort was performed for the secondary components interfacing with the ceramic parts. The redesign effort involved the incorporation of rim seals on the first stage disk, changes to the first stage diaphragm and attachment of the first stage nozzle at the inner shroud, and changes to seals and related parts interfacing with the nozzle outer shroud. The design changes have been detailed elsewhere (van Roode, et al., 1996, 1997).

IN-HOUSE COMPONENT AND ENGINE TESTING

Component Testing

All ceramic components were tested extensively in laboratory rigs prior to engine testing. For example, the blade root configurations were evaluated in an attachment tensile test to establish the optimal blade root angle and compliant layer system. Full blades were tested in a cold spin test at 125% of design load to ensure that they were free of life limiting defects. Nozzles were proof tested in a thermal gradient proof test rig and a mechanical attachment test rig in which stress levels in excess of those in service eliminated defective parts. Details of the proof testing have been previously reported (van Roode, et al., 1996, 1997).

The initial screening of candidate combustor liner materials was performed using a subscale liner test in which key elements of the full scale combustor design are evaluated in a cost-effective but representative geometry. Full scale combustor rig testing was performed with an atmospheric combustor rig to establish that full scale liners can operate under the conditions of temperature that are anticipated in the engine environment. Subsequently, the liners were also tested in a pressurized full scale combustor rig to obtain an early assessment of emissions reduction potential. The liners were subsequently tested in the Centaur 50S engine. Emissions of NOx and CO were promising based on subscale and full scale test data. At full load in the high pressure rig, NOx and CO levels were determined to be <25 ppmv and <5 ppmv, respectively.

Engine Testing

The engine test strategy is based on initially evaluating each ceramic component separately, before testing the components in combination, in the Centaur 50S engine. This methodology minimizes the possibility of secondary damage to downstream prototype ceramic components in the case of an upstream ceramic component failure. The engine tests are initially performed at the baseline TRIT of 1010°C (1850°F) for each ceramic component system prior to testing these components in combination. In subsequent testing, ceramic components are being combined and the engine is operated again at the baseline TRIT. The final test at a TRIT of 1121°C (2050°F) will be conducted with all three ceramic component systems, i.e., the blade, the nozzle, and a set of combustor liners.

The engine used for in-house testing is shown in Figure 7. Table 1 summarizes the test data obtained to date. The tests were conducted at the baseline TRIT of 1010°C (1850°F) of the all-metal engine.

The first ceramic engine tests which started in August 1995 were short (1-2 hrs) and were intended to validate the dovetail blade design. The tests were performed with NT164 and ON-10 silicon nitride dovetail blades. The ceramic components and interfacing secondary components performed as expected and demonstrated good durability. Subsequently, an engine test was conducted with BFG SiC/SiC CFCC liners for a total of 12 hrs at full load over several cycles. This test established that the CFCC material was adequate. Emission levels determined in that test were very promising. NOx levels <15 ppmv and CO levels around 5 ppmv were typically measured at a 3% pilot fuel setting (Smith, et al., 1996, 1997). The measured emission levels were well below the CSGT program goals of 25 ppmv NOx and 50 ppmv CO. The CFCC liners were in good condition following the tests. These initial successful tests with a single ceramic component were followed by engine testing of both ceramic blades and combustor liners simultaneously. A 100 hour endurance test of 62 AS-800 (CC) dovetail blades and enhanced SiC/SiC (DLC) CFCC combustor liners was initiated in November 1996. Two compliant blade attachment systems were evaluated in the test. After 58 hours of cyclic testing, the engine shut down due to failure of the first stage blades. Failure analysis indicated that the origin of the failure was in one of the compliant blade attachment systems which caused the dovetail to pinch in the disk following cyclic engine testing. The alternate blade attachment system remained free in the disk. The attachment system was modified to further eliminate the risk of pinching, and the failed compliant layer system was eliminated (Jimenez, et al., 1998).
A second 100 hour endurance test of 62 AS-800(CC) blades and enhanced SiC/SiC (DLC) CFCC liners was initiated in April 1997. The test included the modifications to the ceramic blade attachment system. The test was performed over a number of days incorporating cold and hot restarts. A total of 12 cold starts and 15 hot restarts were accumulated over the 100 hrs duration of the test. Final inspection revealed the ceramic and interfacing metal parts to be in excellent condition. This engine configuration was then used for the first field test in May 1997. Figure 8 shows the rotor assembly with AS-800 first stage blades prior to engine testing. Figure 9 shows the CFCC outer and inner liners of the combustor following the 100 hr engine test.

Recently, the first test was also conducted in which the SN-88 ceramic nozzle was evaluated. The test lasted for 9 hrs, 1 hr of which was at full load. Some minor chipping was found at the inner and outer shroud areas contacting the metal suggestive of a localized excessive contact stress condition. Redesign efforts are currently underway to alleviate this stress condition (Faulder, et al., 1998). The next engine test of the SN-88 nozzles is planned for March 1998. The main focus of the engine testing will be to combine all three ceramic components, CFCC combustor liners, first stage blades, and first stage nozzles in the engine builds, and to operate the engine at the ultimate design TRIT of 1121°C (2050°F). A final 100 hr
test will be conducted prior to the final 4,000 hr field test scheduled for Phase III of the program.

FIELD TESTING

In May 1997 the CSGT program experienced its most significant accomplishment to-date. The CSGT T5901 Centaur 50 SoLoNOx engine retrofitted with DLC enhanced SiC/SiC CFCC combustor liners and CC AS-800 first stage ceramic turbine blades was shipped to ARCO Western Energy Bakersfield enhanced oil recovery site for the first field test of ceramic hot section components in an industrial gas turbine engine. This engine replaced one of ARCO's existing gas turbines, a model T5501 Centaur 50, operated with water injection for NOx control. ARCO's control system was upgraded to allow operation in the SoLoNOx mode.

The field test started on May 21. A view of the test engine at the field test site is shown in Figure 10. The engine operated at the 1010°C (1850°F) TRIT of the standard all-metal engine to demonstrate performance under typical industrial operating conditions. The CSGT engine was fully operational with normal steam and electrical power production. Boroscope inspections, conducted after 212 hours and 533 hrs showed no change in the appearance of the CFCC combustor liners and first stage ceramic turbine blades as compared to the appearance after the 100 hour acceptance test at Solar. The field test duration was scheduled for 2000 hours of maximum load operation with periodic boroscope inspections.

![FIG. 10 - CSGT CENTAUR-50S ENGINE AT ARCO FIELD TEST SITE](image)

On July 1, 1997, after 948 hours of full load operation, the CSGT engine shut down due to turbine overspeed. After several failed attempts to restart the engine, a boroscope inspection revealed that the 62 turbine blade airfoils had failed during service, which has now been attributed to impact damage from a locating pin from the inner liner of the combustor. ARCO's water-injected Centaur 50 T5501 was reinstalled and the CSGT engine was returned to Solar for failure analysis.

Failure analysis of the blades indicated that all of the fractures were above the blade platform and none of the dovetails were pinched in the disk (which was the cause of the previous blade failure), indicating that the redesign of the dovetail attachment was successful. The compliant layer attachment system appeared to have performed as designed. There was no evidence of contact on the first stage tip shoes. During teardown of the combustor, a locating pin (0.75 in. x 0.375 in. diam. tool steel) used during assembly of the combustor dome was found to be missing for the inner liner. The missing pin was at the bottom dead center location. Witness marks inside the housing of the inner liner indicated that the pin had moved to the aft end of the liner to a location near the 0.400 dilution holes. It was determined that the pin exited one of the dilution holes and continued through the first stage nozzles into the ceramic turbine blades. Selected AS-800 blade roots from the ARCO field test failure were sent to ORNL for examination of the fracture surfaces. Evaluations to date have shown no sign of slow crack growth in the remaining blade airfoil.

The ceramic combustor liners remained intact following the engine shutdown. Over 1000 hrs of cumulative engine test data (test cell and field test data) to-date have demonstrated that a simple modification to the Centaur 505 SoLoNOx combustor, involving replacement of the currently louvre-cooled metal liners with uncooled liners fabricated from continuous fiber-reinforced ceramic composite (CFCC) materials, results in significantly improved levels of NOx and CO at the 1850°F TRIT of the Centaur 50S engine. This reduction in emissions is a significant milestone for the program, as well as for future gas turbines, and becomes particularly important as the drive to reduce "greenhouse gases" increases. NOx levels from 10-15 ppmv and CO levels of around 5 ppmv have routinely been measured over the 50-100% load range for the CSGT engine operating on natural gas at ARCO. The outer CFCC combustor liner showed minor indications of oxidation following the field test. The inner CFCC liner exhibited a higher degree of uniform oxidation which will limit the life of the liner. The maximum inner liner temperature measured was 2170°F, which was about 100-150°F higher than the outer liner.

The next field test of ceramic components is scheduled for March 1, 1998 at ARCO Western Energy. This test will again contain 62 AS-800 (CC) dovetail blades and enhanced SiC/SiC (DLC) CFCC combustor liners. The dovetail angle has been changed from 55 degrees to 15 degrees to further reduce the risk of pinching. A 100-hour engine acceptance test of the 45 degree dovetail AS-800 blade was completed in January 1998. The blades appear in excellent condition, showing no signs of pinching in the disk.

Several changes have been made to the CFCC combustor liner system in an attempt to reduce the oxidation of the enhanced SiC/SiC liners experienced during the field test at ARCO. Design changes to the metallic portion of the liners to improve the conduction path from the CFCC liners to the metal housings have resulted in a temperature drop of about 130°F for the CFCC liners. Material changes to the CFCC liners include using Hi-Nicalon fibers (which are stronger and more stable at higher temperatures and have higher thermal conductivity than the previous ceramic-grade Nicalon fibers), increasing the density of the CFCC liners, and doubling the thickness of the protective seal coat used for the CFCC liners. The liners will be tested in Solar's atmosphere rig in late January in preparation for the next 2000 hour field test at ARCO.

SUMMARY

A Solar Turbines Incorporated Centaur 50S gas turbine is being retrofitted with ceramic first stage blades, first stage nozzles, and combustor liners for improved performance and lower emissions. The component designs have been completed and have been validated in rig and engine testing. A Centaur 50S engine with ceramic first stage blades and combustor liners started a 2000 hr field test on May 21 at the baseline TRIT of 1010°C (1850°F) of the all metal engine. The engine field test accumulated 948 hours of full load operation prior to engine shutdown due to foreign impact damage of the first stage AS-800 turbine blades. The impact damage occurred due to a metallic locating pin used during combustor assembly impacting the first stage blades. The metallic locating pin has been eliminated and a second 2000 hour field test of ceramic blades and a modified CFCC combustion liner system has been scheduled for March 1998. Additional field testing of CFCC combustor liners, ceramic blades, and ceramic nozzles at an increased TRIT of 1121°C (2050°F) is planned for late 1998.
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